



Knowledge-Aided Sensor Signal Processing
and Expert Reasoning

“Stacking the Odds for the Warfighter”



2nd Annual
KASSPER Workshop
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* All material derived from sources previously cleared for Public Release



Discussion Points



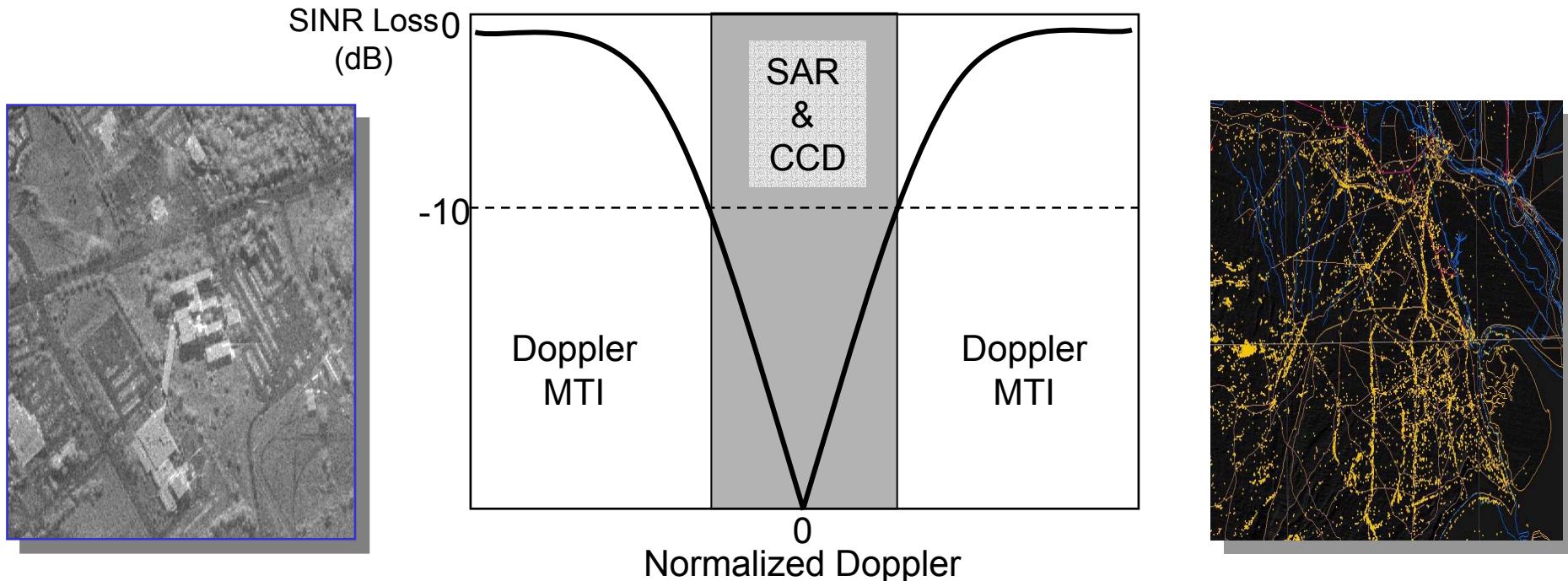
- “Real-world” clutter environments
 - Problem is particularly acute for GMTI applications
 - Examples of deleterious impact
 - “Iceberg” effect; “Fat tails”; Dense target backgrounds; RFI;
- KASSPER: It’s an “architecture” NOT an “algorithm”!
 - Environmental context is key to efficient adaptation
 - Sensors, like humans, benefit from context!
 - Key enablers: “look-ahead” scheduling and resource allocation
 - Multiresolution philosophy: blurring the boundaries between SAR and GMTI
 - KASSPER as a modern manifestation of the “Bayesian” method!
- Goldilocks algorithm?
 - KASSPER “AND” Robust STAP Algorithms (Not either/or)
- Performer Highlights:
 - Excellent progress in ‘02
- The DARPA KASSPER Challenge: Creatively explore the possibilities
 - Re-examine entire adaptive signal processing paradigm with an eye towards maximizing knowledge-aided “robust” methods
 - What is “implementable”? 2010? 2020?
 - Environmentally aware sensors have a future!



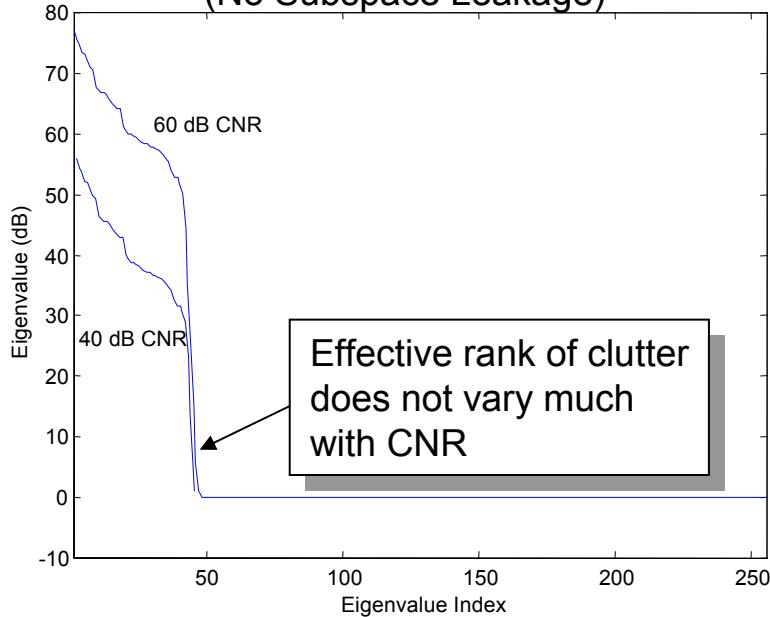
Multiresolution Framework for Tactical GMTI



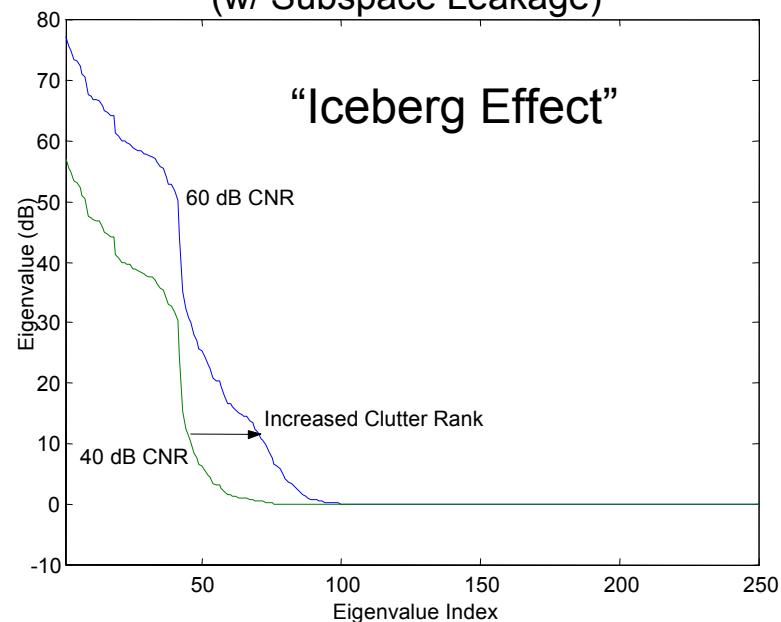
- “Real-world” ground targets exhibit variable range-rate (stops, turns, etc.)
- To maintain “continuous track” of a critical target, radar must “track through null”
- Requires “seamless” integration of GMTI, SAR, & CCD modes
 - SAR & CCD are generally not wide area surveillance modes
- Lots of opportunities for KASSPER knowledge sources across modes
 - SAR can identify strong clutter discretes
 - GMTI can locate roads & other background traffic



Clutter + Noise Eigenspectrum
(No Subspace Leakage)



Clutter + Noise Eigenspectrum
(w/ Subspace Leakage)



- Thus the required rank of the STAP processor (adaptive DOFs) varies with CNR (“Spectral heterogeneity” problem)
 - A fixed-rank STAP processor will therefore either over- or under- null clutter
 - Overnulling clutter leads to poor MDV
 - Undernulling clutter leads to poor SINR and increased P_{fa}



STAP with Priors



- A simple model for nonstationarity

$$\text{Total Received Signal} \rightarrow \mathbf{X} = \mathbf{x}_q + \mathbf{x}_d + \mathbf{n} \in \mathbb{C}^{NM}$$

Quiescent Clutter Background
↓
 \mathbf{x}_q
White Noise
↓
 \mathbf{x}_d
↑
Deviation Clutter Term

$$\text{cor}(\mathbf{X}) = \text{cor}(\mathbf{x}_q) + \text{cor}(\mathbf{x}_d) + \sigma^2 I \in \mathbb{C}^{NM \times NM}$$

↑
“Colored” Loading Term

STAP with Priors (Cont.)

- Example: Clutter “Discrete” with Uncertainty

Deterministic Steering Vector

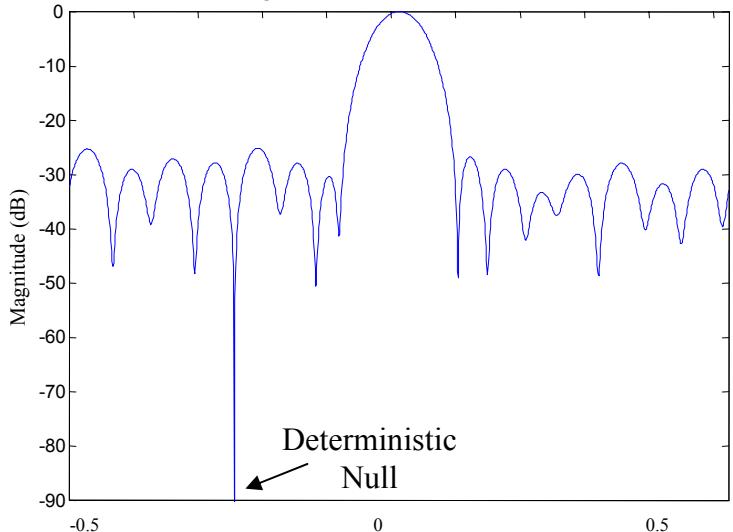
$$\mathbf{x}_d = \mathbf{d} \circ \mathbf{t}$$

“Random” Vector Modulation
(accounts for errors)

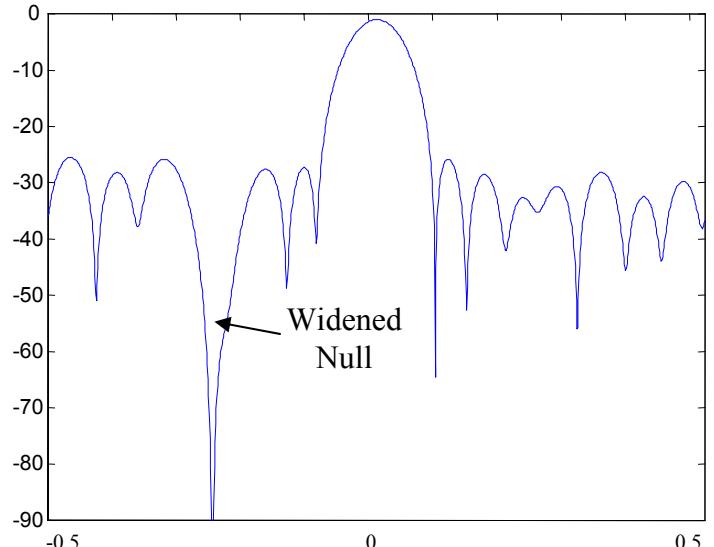
$$\begin{aligned} \text{cor}(\mathbf{x}_d) &= \text{cor}(\mathbf{d} \circ \mathbf{t}) \\ &= \text{cor}(\mathbf{d}) \circ \text{cor}(\mathbf{t}) \end{aligned}$$

$$= \mathbf{d}\mathbf{d}' \circ T$$

Covariance Matrix Taper (CMT)
(generally full-rank)



CMT to Account for Discrete Uncertainty

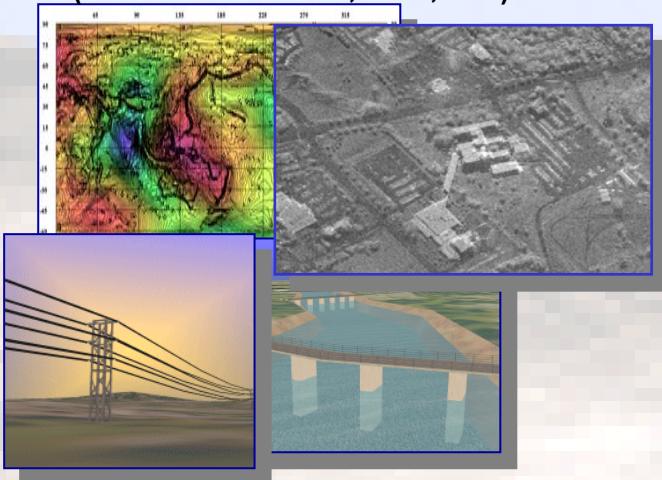




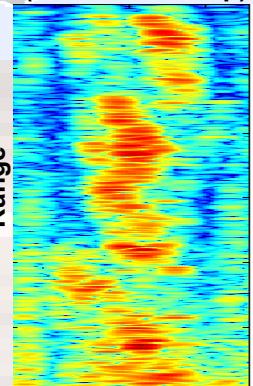
KASSPER Enabled by a Confluence of Emerging Technologies



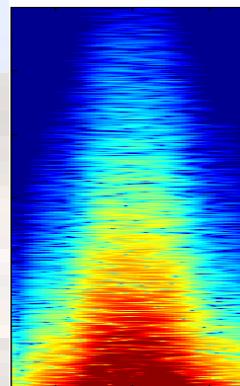
Radar Environmental Knowledge Bases
(DTED/DFAD/LCLU, SAR, etc.)



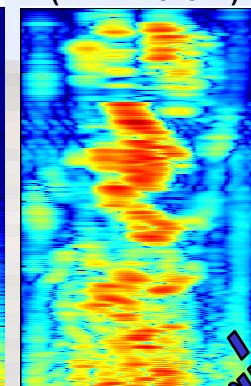
Measured
(DARPA Mtn Top)



Bald Earth



Predicted
(DTED Level-1)

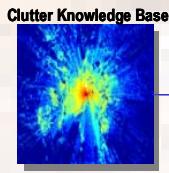


Range

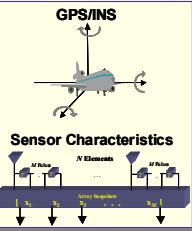
Doppler

0 10 20 30 40 50 60 70
relative power (dB)

KASSPER

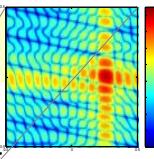


Clutter Cell Returns $\{r_i\}$



$$R_{KA} = \sum_i \gamma_i^2 C_i C_i' + \sigma^2 I$$

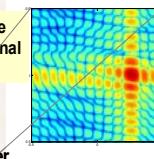
Sum Over Clutter Cells



Nonstationary Clutter (plus Signal)

X

$$X \xrightarrow{R_{KA}^{-\frac{1}{2}}} Y = R_{KA}^{-\frac{1}{2}} X$$



Reduced-Rank Conventional Filter

$$\hat{R}_{SMI}^{-\frac{1}{2}} \xrightarrow{} Z = \hat{R}_{SMI}^{-\frac{1}{2}} Y$$

Detector

1980

Exponential Growth in Enabling Technologies

Physical Databases

Real-Time Database

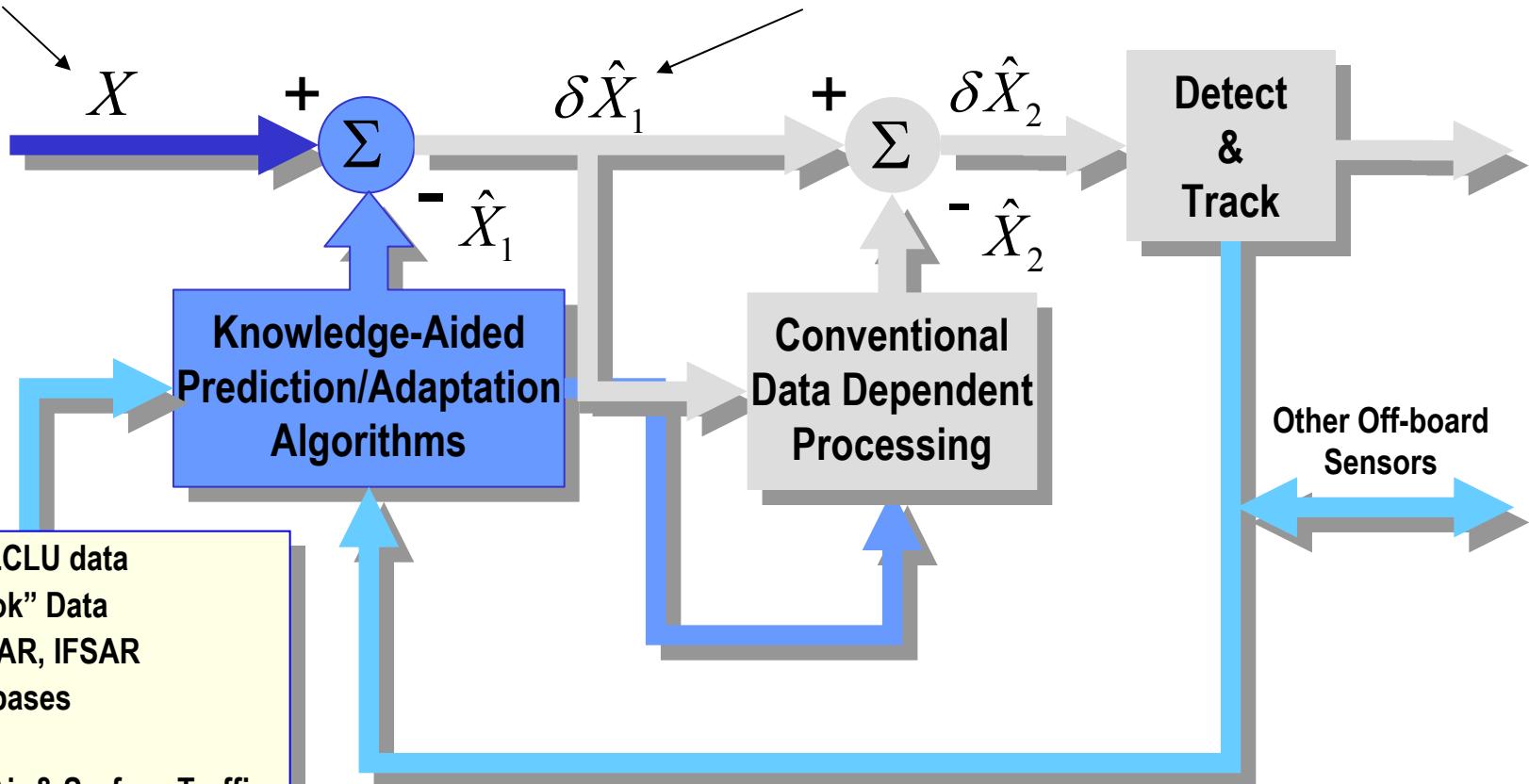
EM Modeling Tools

HPEC

2000

Highly Nonstationary, Complex Interference

Better Conditioned Signal Residue



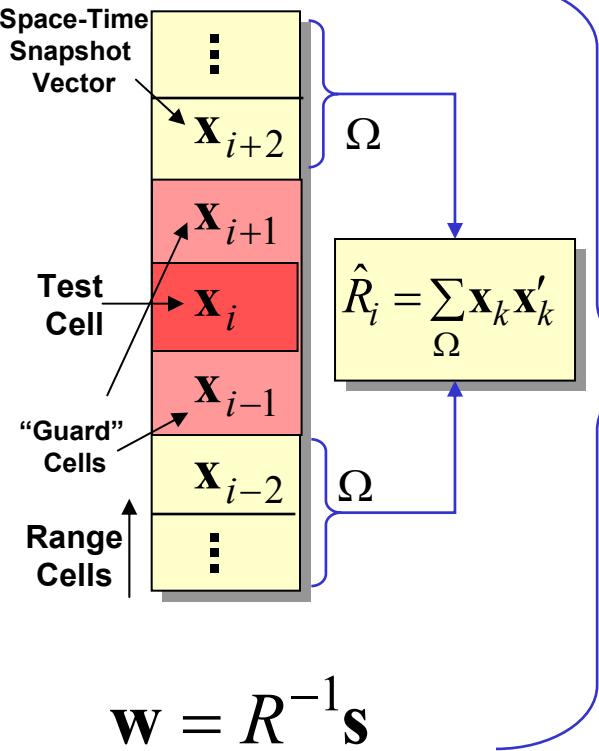
- DTED/DFAD/LCLU data
- Previous “Look” Data
 - GMTI, SAR, IFSAR
- Cultural Databases
- Roadways
- Background Air & Surface Traffic
- Ownship Position, Velocity, Orientation
- System Calibration Information
- EMI Data
- Other

In case I forgot to mention:
“It’s an architecture NOT an algorithm!”

Conventional vs. KASSPER HPEC Processing

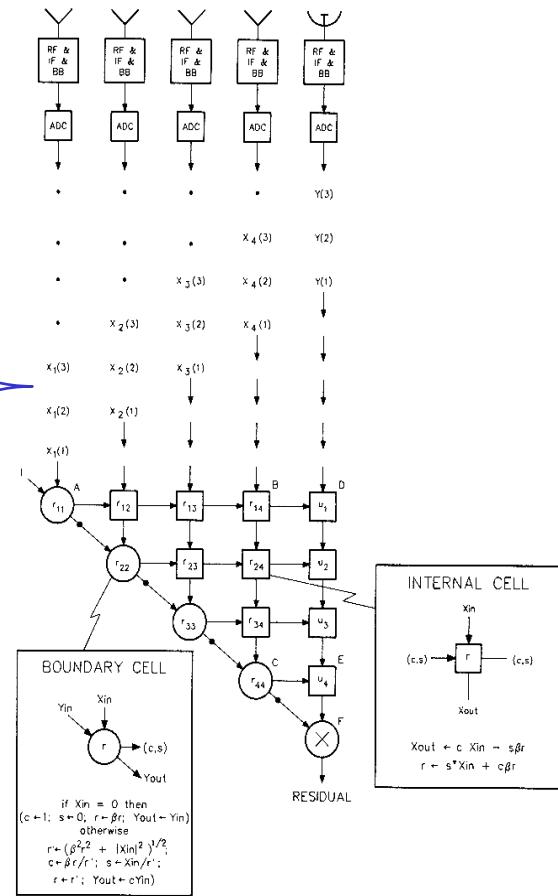


Conventional Space-Time Filtering



$$\mathbf{W} = R^{-1} \mathbf{s}$$

Highly Parallel Systolic Array Implementation (Achieves 100's to 1000's of GFLOPS)

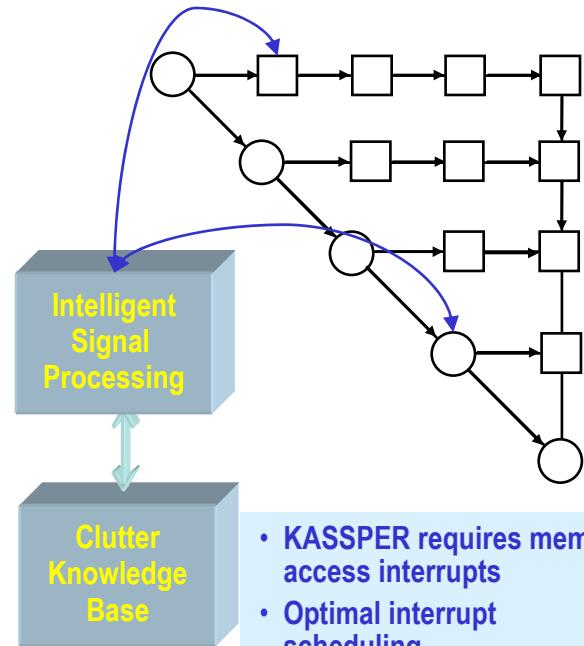


QR Factorization w/ Back substitution

(from *Antenna-Based Signal Processing Techniques for Radar*, A. Farina, Artech House)

KASSPER HPEC Challenge:
Optimizing adaptation by injecting environmental knowledge
“intelligently” into the front-end signal flow

First Gen Real-Time KASSPER HPEC



- KASSPER requires memory access interrupts
- Optimal interrupt scheduling
- Optimized ISP
- “Look-Ahead” scheduling



“Look-Ahead” Scheduling Addresses Memory Latency Issues



Problem:

Capacity
Access Time

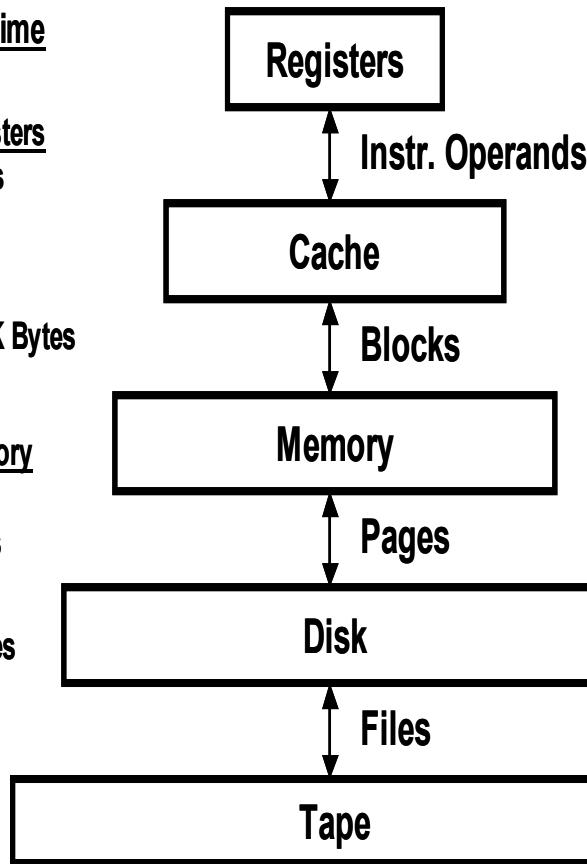
CPU Registers
100s Bytes
<1 ns

Cache
10s-100s K Bytes
1-10 ns

Main Memory
M Bytes
100-300 ns

Disk
10s G Bytes
10 ms

Tape
Infinite
sec-min



Staging Transfer Unit

Prog./Compiler
1-8 Bytes

Cache Controller
8-128 Bytes

OS
512-4K Bytes

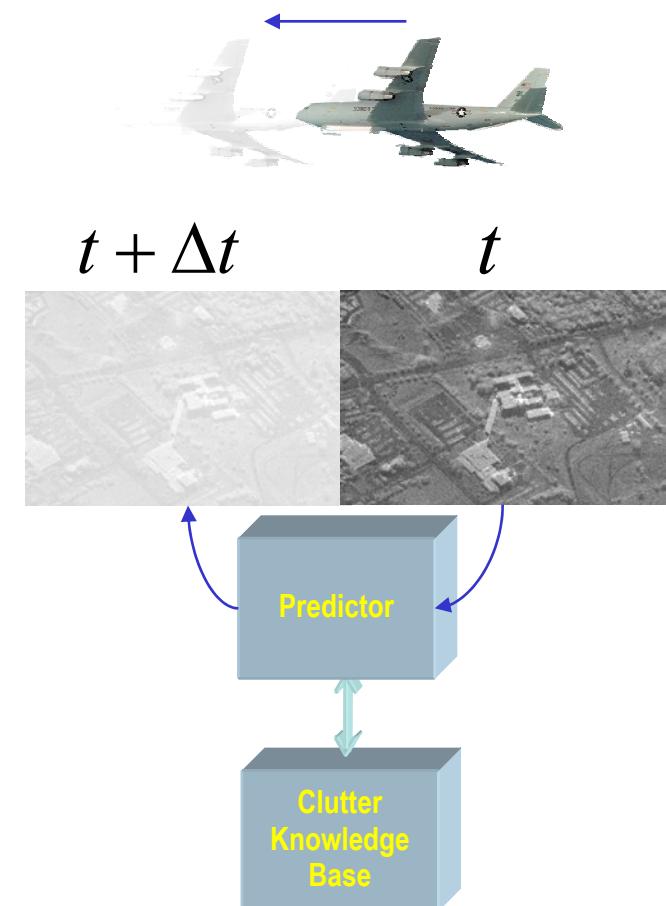
User/Operator
MBytes

Faster Speed Higher Cost

Larger Size Lower Cost

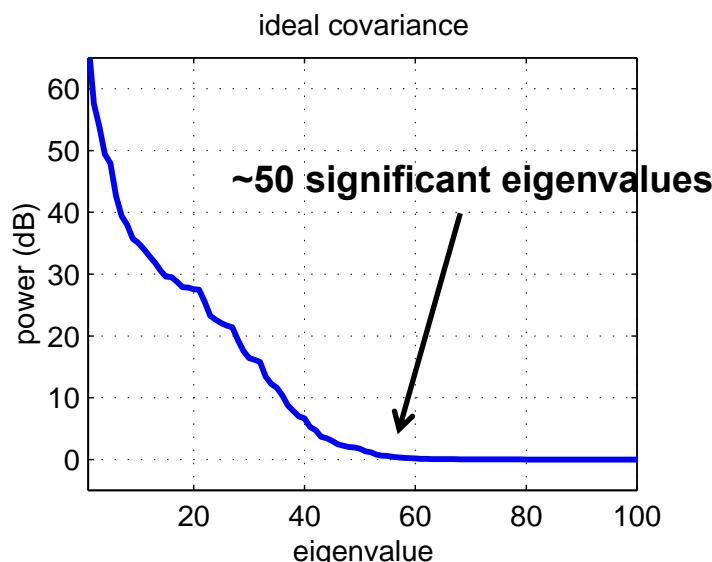
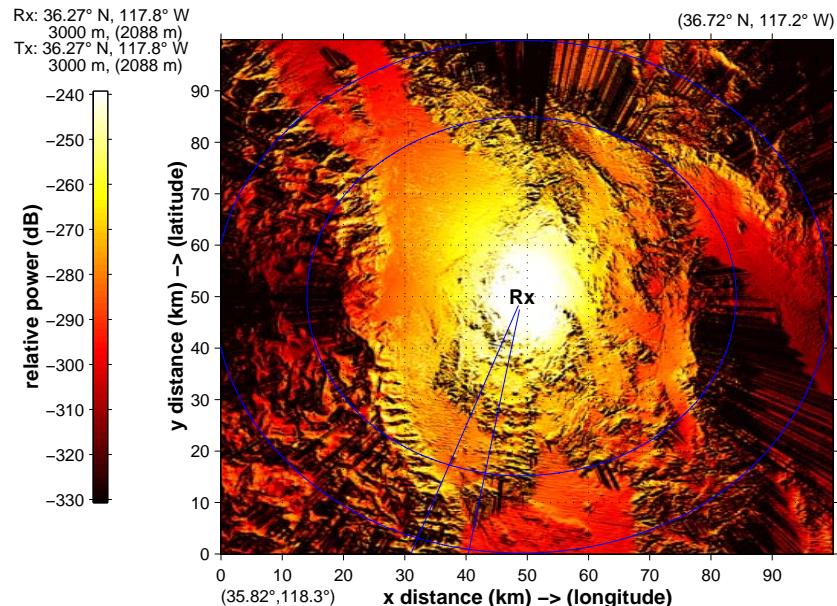
Solution:

KASSPER
“Look-Ahead”
Interrupt Scheduling





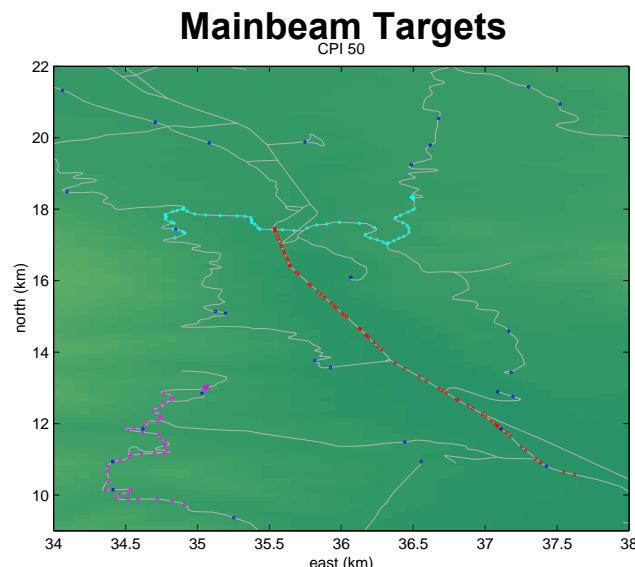
Workshop '02 Simulated Data Cube



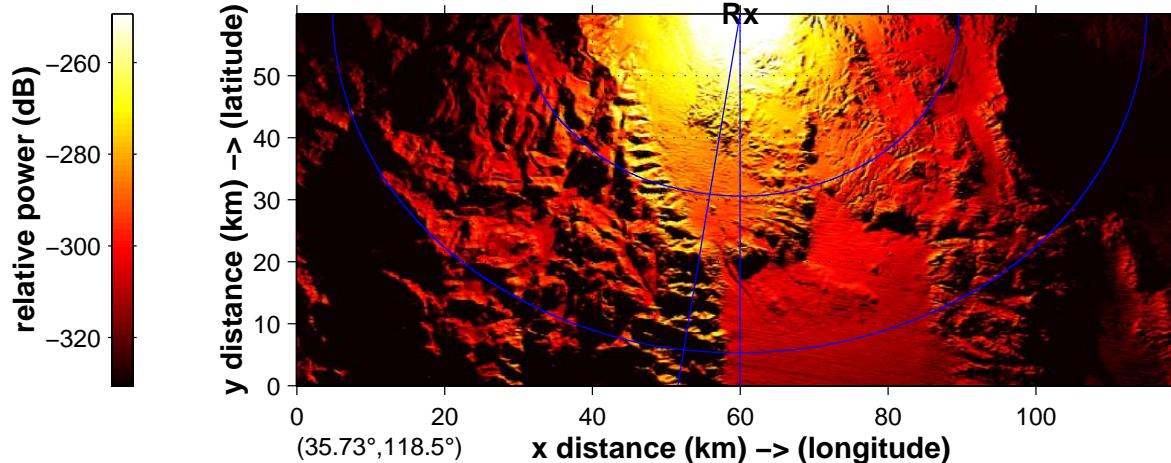
Parameter	Value
RF frequency	1240 MHz
Bandwidth	10 MHz
PRF	1984 Hz
Peak Power	15 kW
Duty factor	10%
Noise figure	5 dB
System losses	9 dB
Platform speed	100 m/s
Platform altitude	3 km
Transmit aperture	8 vertical x 11 horizontal
Receive aperture*	8 vertical x 1 horizontal
Horizontal antenna spacing	10.9 cm
Vertical antenna spacing	14.07 cm
Number of receive sub-apertures	11
Front-to-back ratio	25 dB

- Initial site-specific data set generated under KASSPER program
- Distributed at '02 Workshop
- Heterogeneous clutter, ground vehicles, ICM, calibration errors

Multiple CPI Simulated Data Set

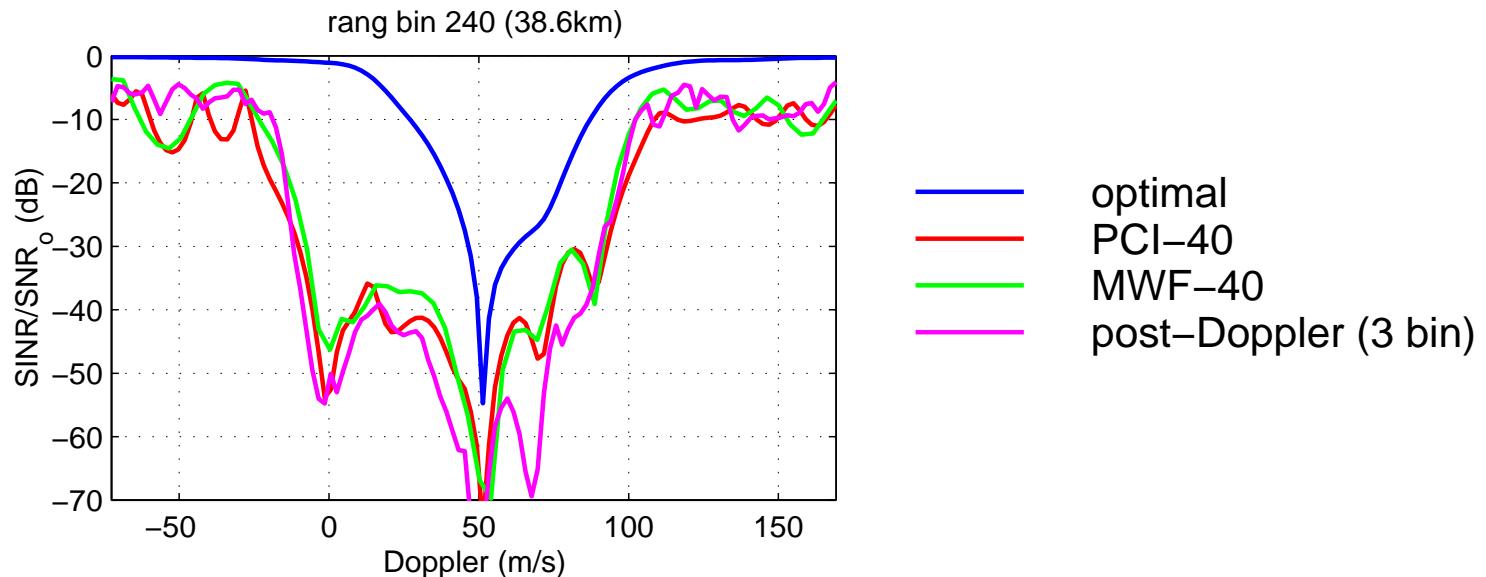


Rx: 36.27° N, 117.9° W
 5339.3891 m, (1645 m)
 Tx: 36.27° N, 117.9° W
 5339.3891 m, (1645 m)

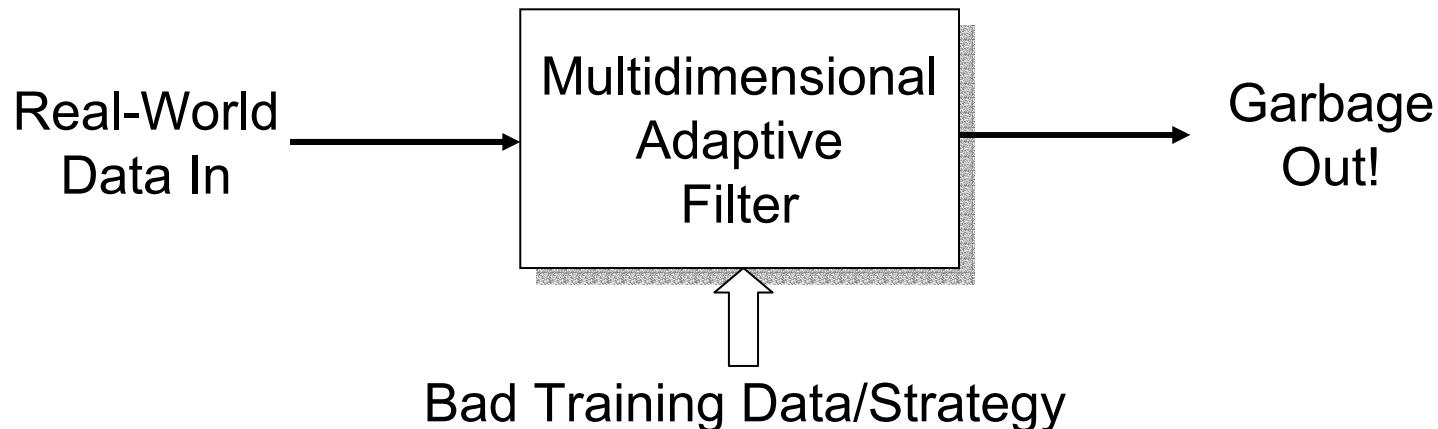


- 30 Dwells Simulated (3 CPIs per dwell)
 - 12 subarrays, 32 pulses
 - X-band
 - Heterogeneous clutter, ground vehicles, ICM, calibration errors
 - Ideal covariance for a single CPI

Conventional STAP Training



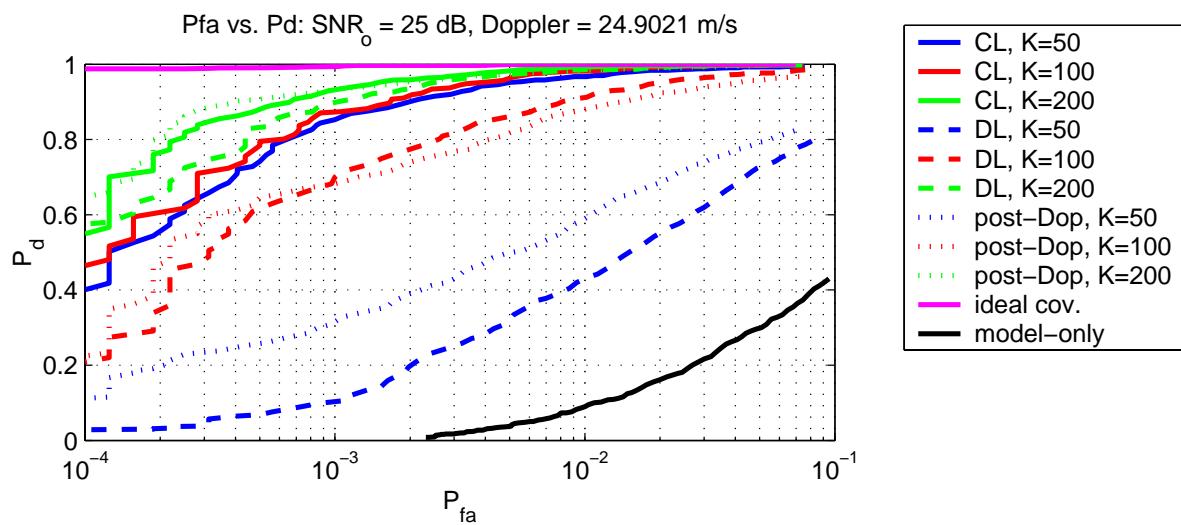
- MWF and PCI : 40 DoFs and 100 training samples
- Post-Doppler: 3 bins, 11 elements (33 DoFs) and 66 training samples
- KASSPER '02 Workshop Datacube



Colored Loading Algorithm

$$\mathbf{w} = \frac{(\mathbf{R}_{xx} + \beta_d \mathbf{R}_c + \beta_L \mathbf{I})^{-1} \mathbf{v}}{\mathbf{v}^H (\mathbf{R}_{xx} + \beta_d \mathbf{R}_c + \beta_L \mathbf{I})^{-1} \mathbf{v}} = \frac{(\mathbf{R}_{xx} + \mathbf{Q})^{-1} \mathbf{v}}{\mathbf{v}^H (\mathbf{R}_{xx} + \mathbf{Q})^{-1} \mathbf{v}}$$

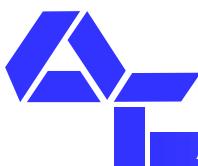
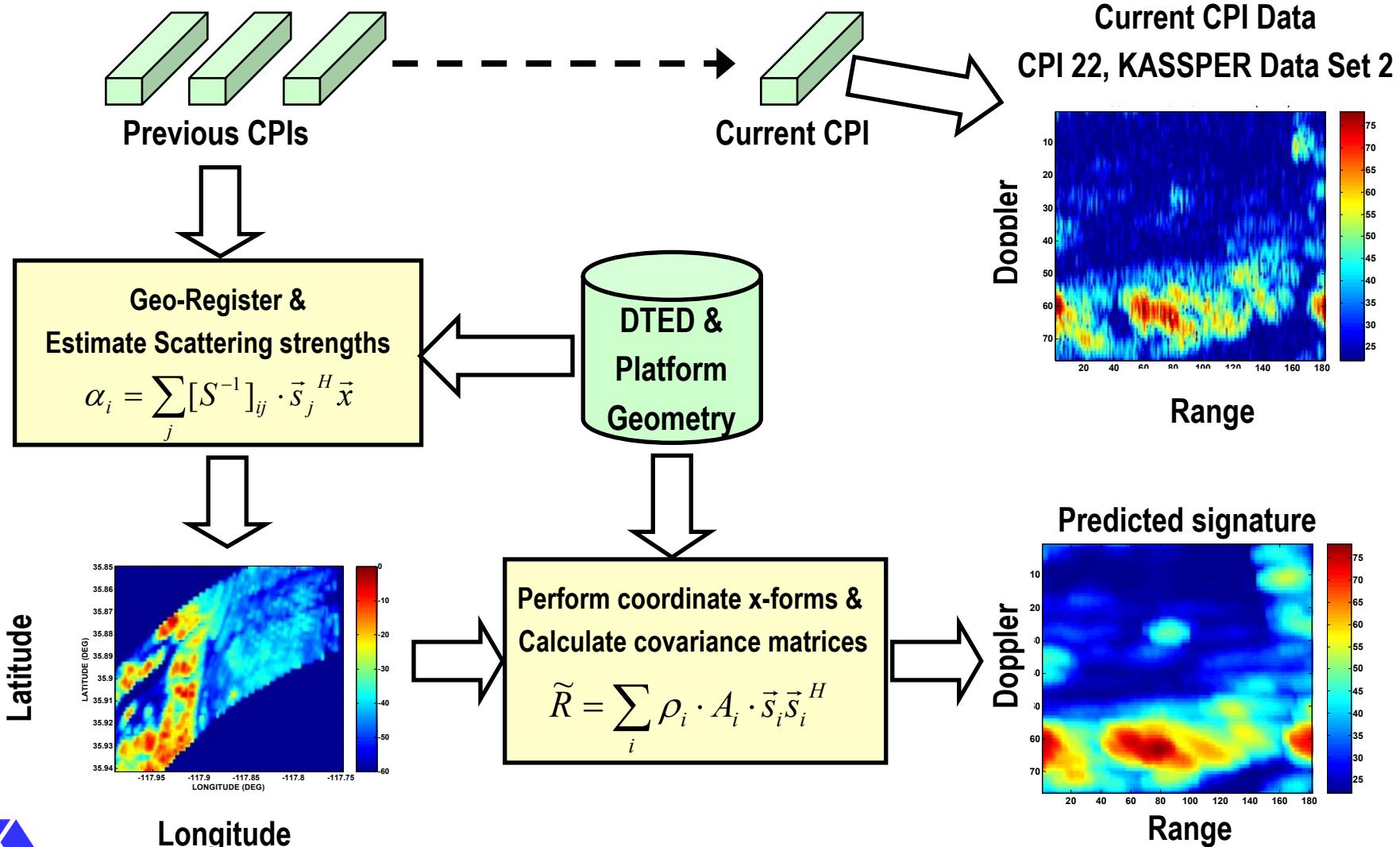
↑ ↑ ↑
 sample covariance clutter covariance Model diagonal loading
 "colored loading"



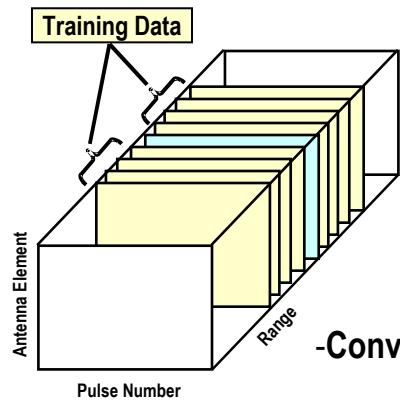
- Algorithm is derived by placing constraints on the *a priori* clutter covariance model
- Can be interpreted as a deterministic pre-filter
- Faster convergence → effective increase in clutter samples
- Readily implemented in the data domain
- Many possible forms for the clutter covariance model
 - Discretes
 - Ground clutter subspace



Utilizing Past-CPI Data to Predict Clutter Statistics



Current CPI Data-Cube



Incorporate knowledge into STAP weight vector calculation

Calculate STAP weights



-Conventional covariance estimates

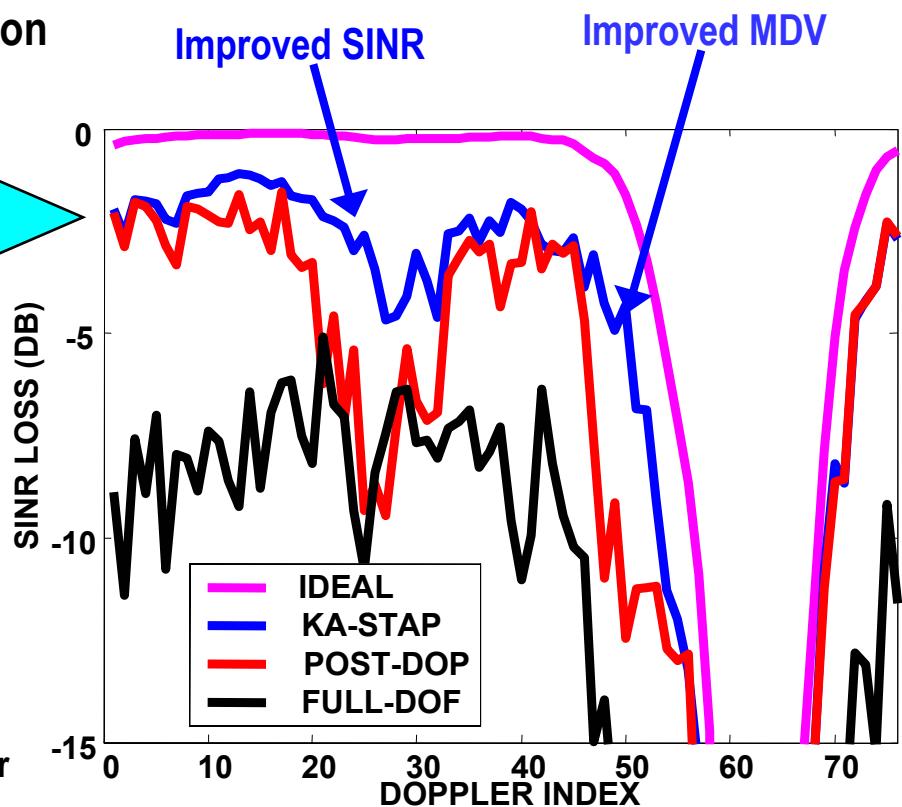
$$\hat{R} = \frac{1}{K} \sum_i \vec{x}_i \vec{x}_i^H + \gamma \cdot I$$

-Knowledge-derived covariance matrices

$$\tilde{R} = \sum_i \rho_i \cdot A_i \cdot \vec{s}_i \vec{s}_i^H \circ T + \gamma \cdot I$$

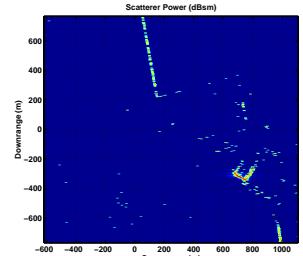
-Tracker predictions of target range/Doppler locations

SINR Loss Performance
(KASSPER Data Set 2, CPI 22, range 1035)





Pre-Filtering Discretes Using APTI Data

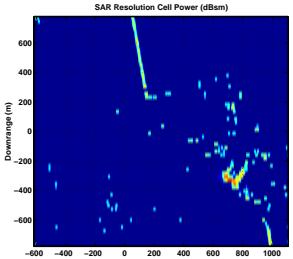


100 MHz SAR Image

CLEAN

Discrete data

Noncoherent Decimation



BW = 6 MHz

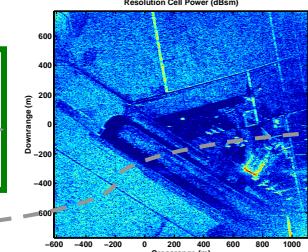
STAP Simulation

Blue (left side)
is the discrete
pre-filtering
chain

Blue (left side)
is the discrete
pre-filtering
chain

Green (right side) is
emulation used to
synthesize GMTI data
from SAR imagery

Coherent Decimation



STAP Emulation

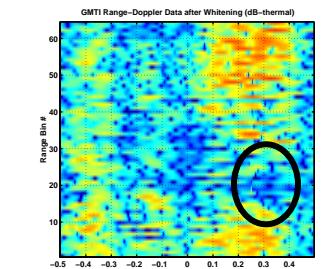
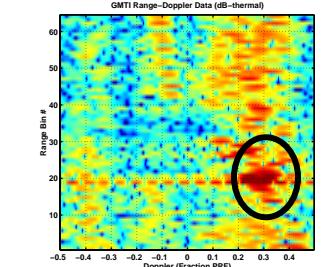
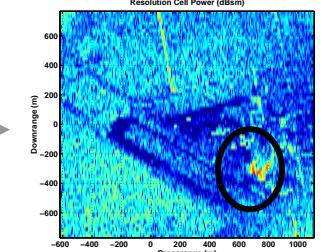
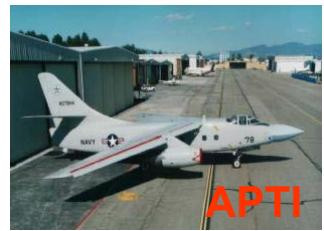
GMTI
Data
Cube

$R^{-1/2}$ or
 $(I - UU^H)$

Whiten

Angle
Steer

Range-Doppler
Maps

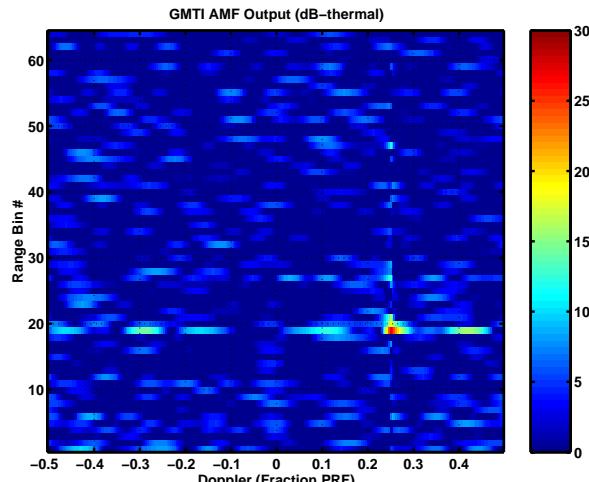




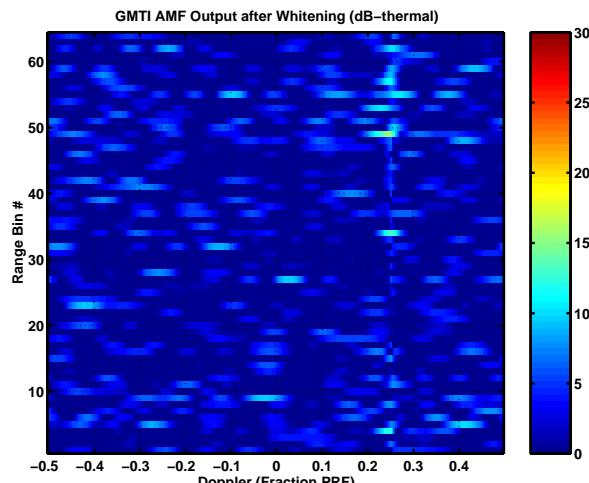
Pre-filtering Followed by Conventional STAP



Adaptive Matched Filter

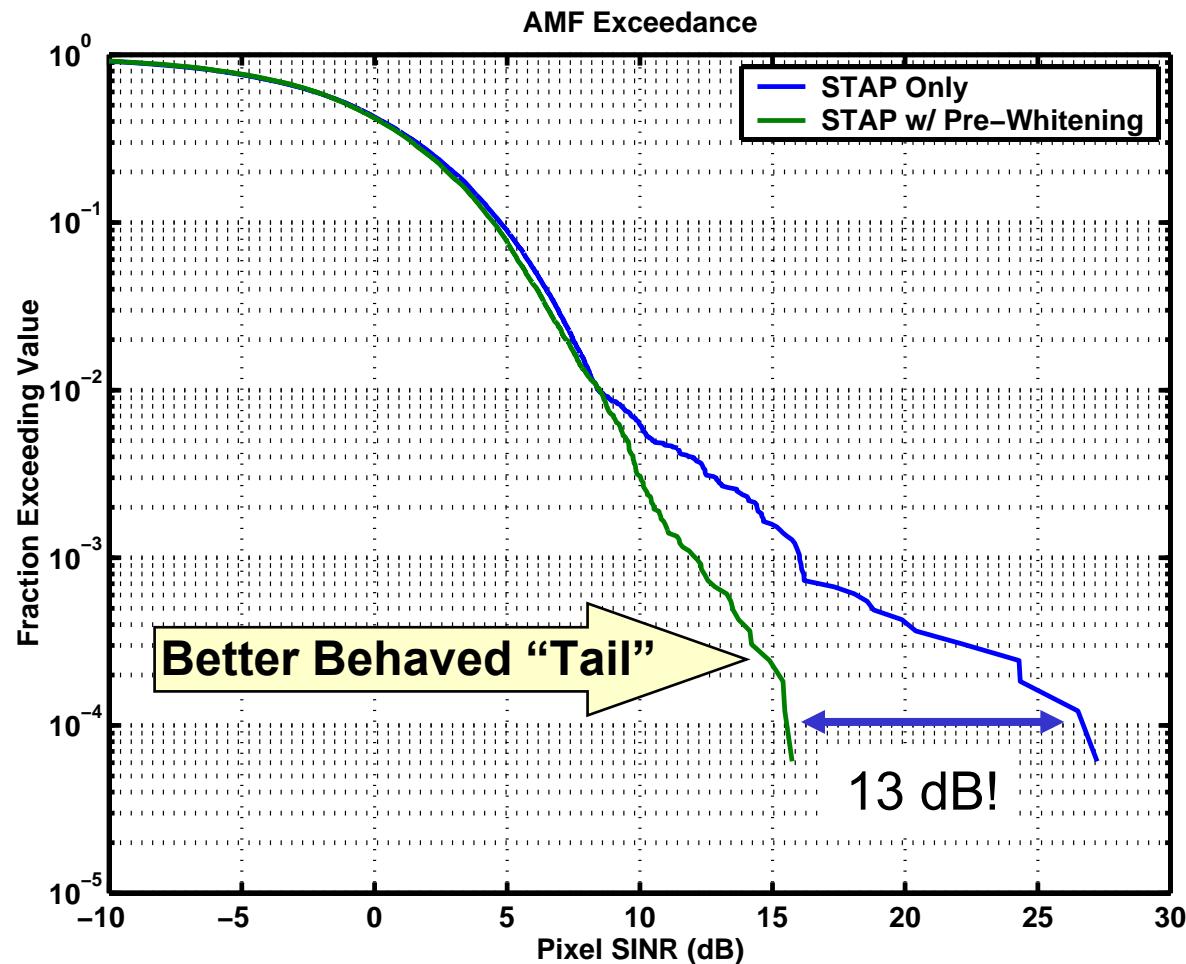


Without Prefiltering



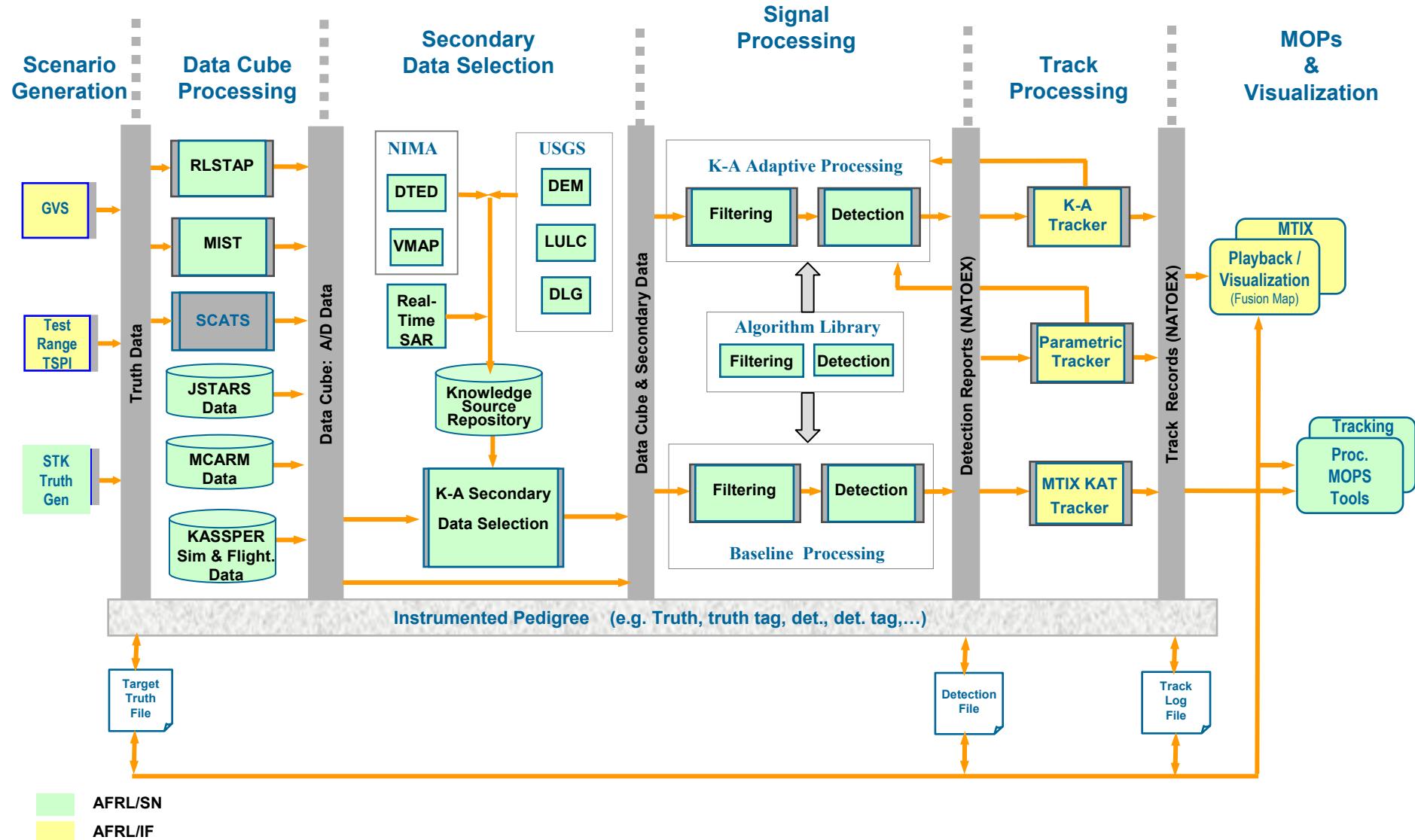
With Prefiltering

Pre-Filtering Reduces The “Tail” of the Exceedance Function



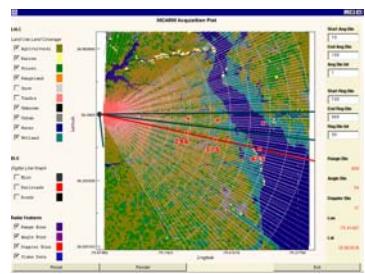
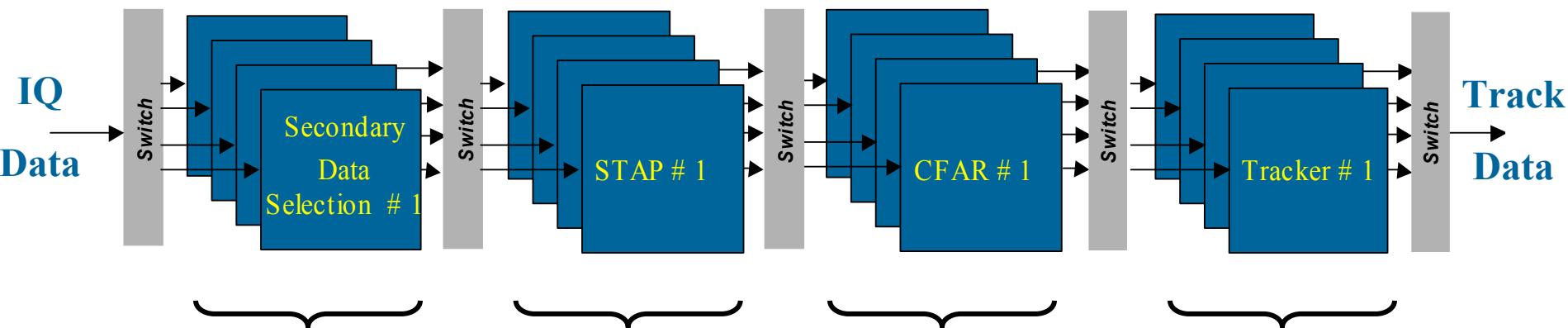


SPEAR Testbed



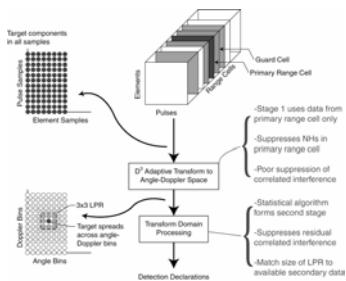
KASSPER Algorithm Evaluation

Secondary Data Selection



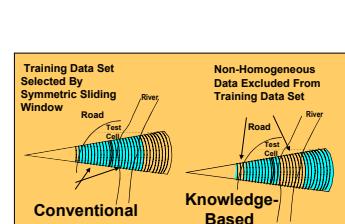
Secondary Data Selection # 2

STAP Algorithm Selection



STAP Algorithm # 3

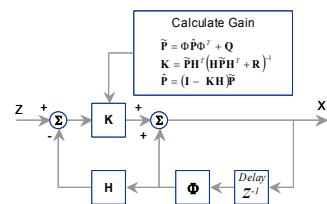
Detection Algorithm Selection



CFAR Algorithm # 1

Tracker Selection

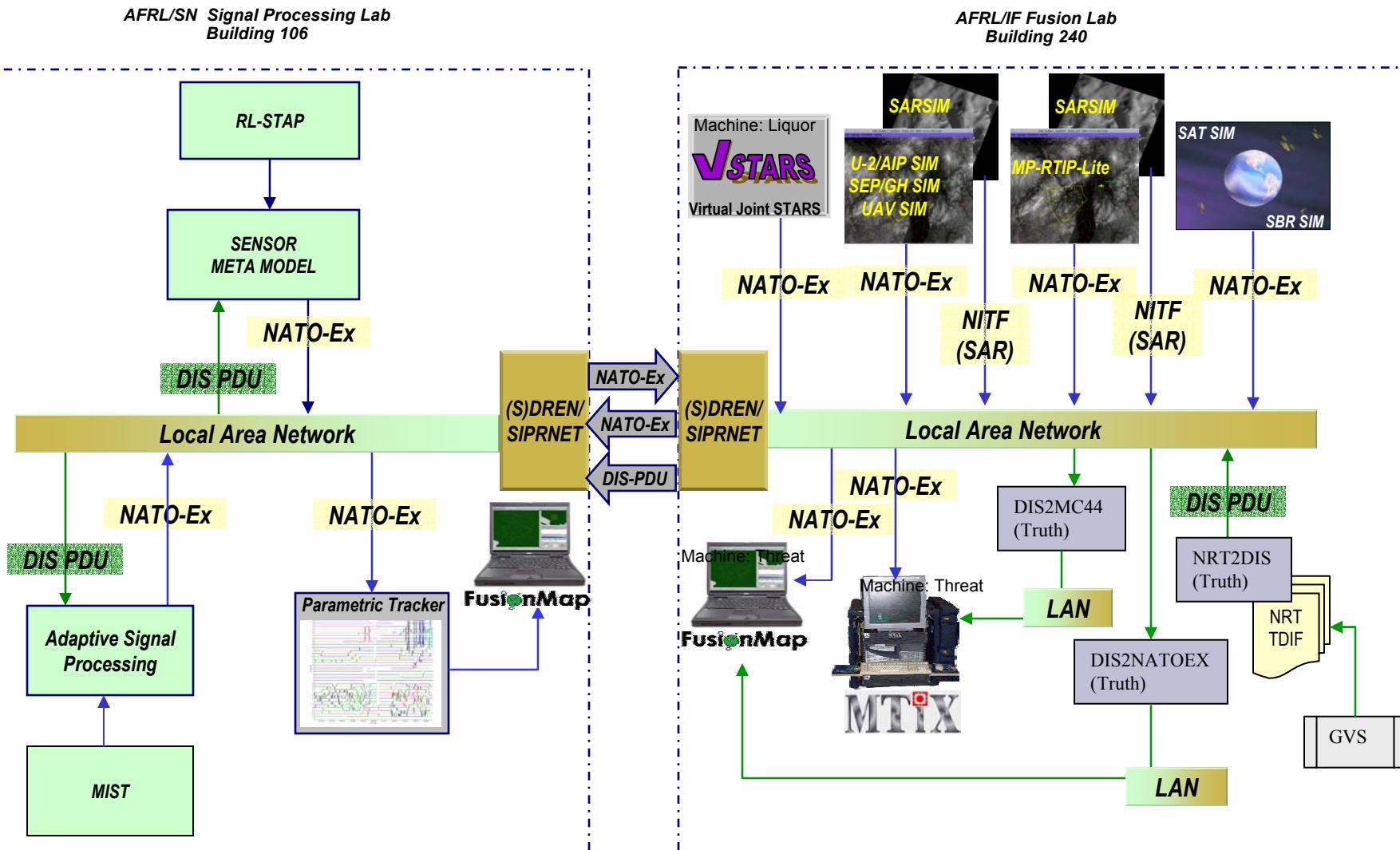
$$\begin{aligned}\tilde{\mathbf{X}} &= \Phi \cdot \hat{\mathbf{X}} + \int (\Phi \cdot \mathbf{B} \cdot \mathbf{u}) dt \\ \tilde{\mathbf{P}} &= \Phi \dot{\mathbf{P}} \Phi^T + \mathbf{Q} \\ \mathbf{K} &= \tilde{\mathbf{P}} \mathbf{H}^T (\mathbf{H} \tilde{\mathbf{P}} \mathbf{H}^T + \mathbf{R})^{-1} \\ \hat{\mathbf{P}} &= (\mathbf{I} - \mathbf{K} \mathbf{H}) \tilde{\mathbf{P}} \\ \hat{\mathbf{X}} &= \tilde{\mathbf{X}} + \mathbf{K} [\tilde{\mathbf{Z}} - \mathbf{H} \tilde{\mathbf{X}}]\end{aligned}$$



Tracker # 4



KASSPER Test & Evaluation Testbed



Courtesy of Jon Jones AFRL/IFEA



KASSPER

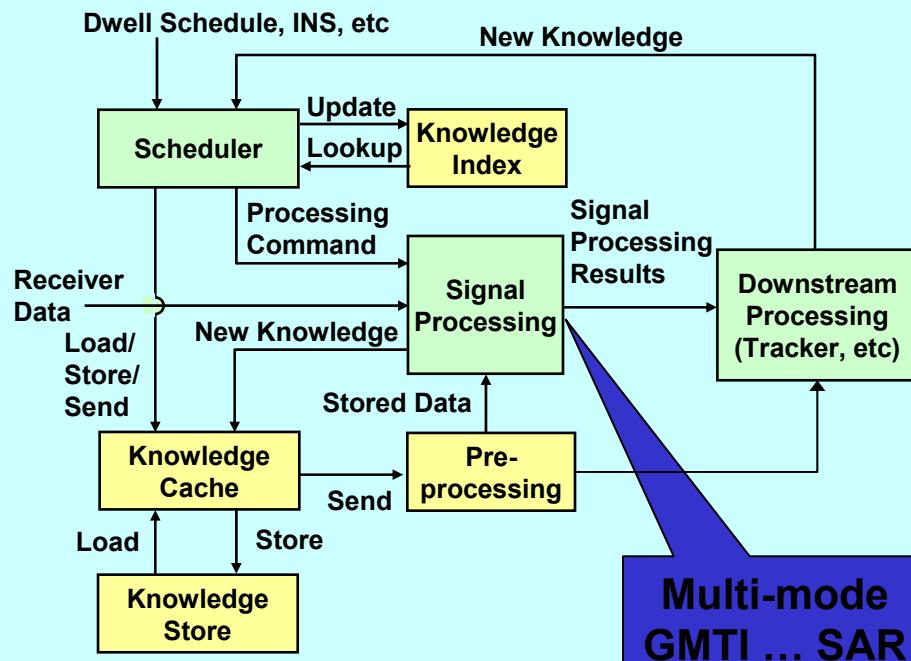
Real-Time Processor Testbed



REAL-TIME PROCESSING CHALLENGES

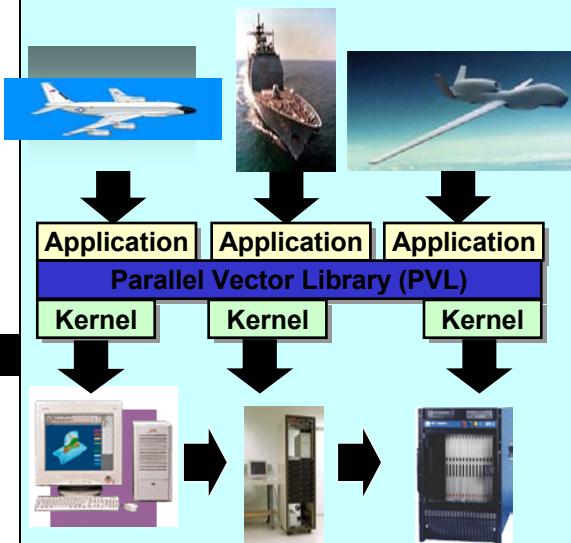
- Look-ahead scheduling
- Appropriate use of new concepts with available processing resources
- Intelligent caching of knowledge databases

PARALLEL PROCESSING ARCHITECTURE



- Support knowledge storage, retrieval, and use
- Support the continuum between GMTI and SAR processing
- GMTI chain up and running on Parallel Processor

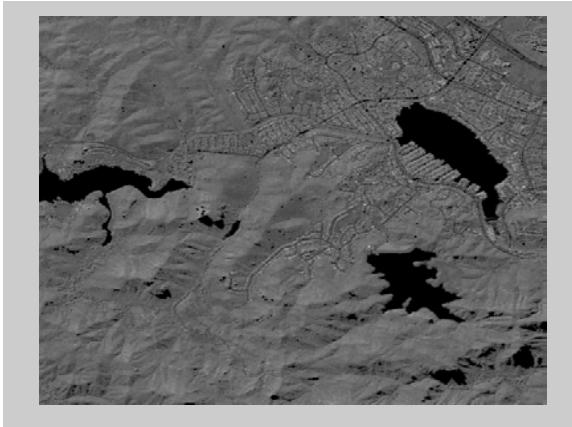
PARALLEL VECTOR LIBRARY



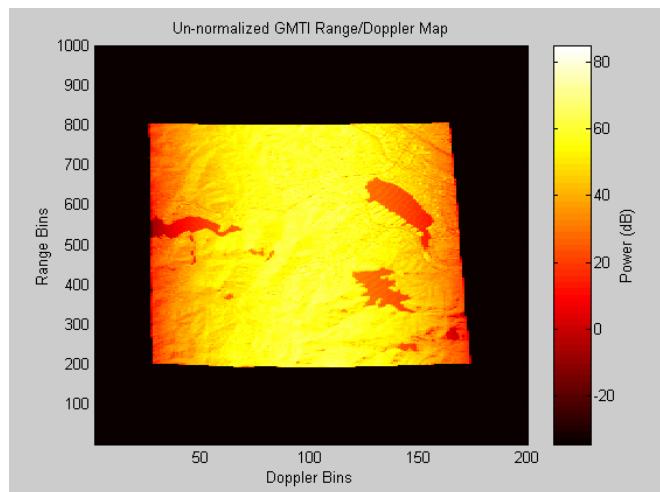
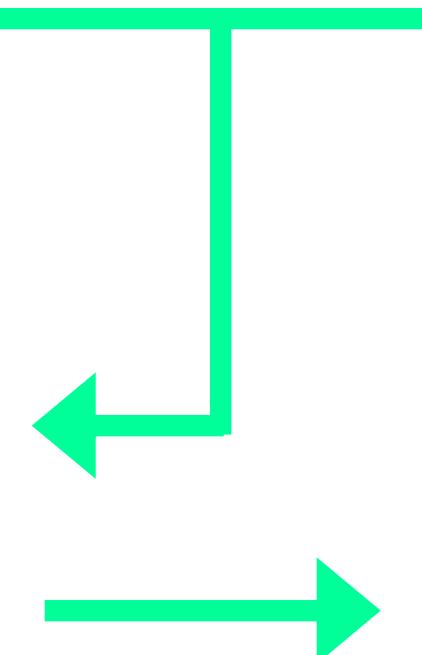
- Rapid Prototyping
- High Level Abstractions
- Scalability
- Productivity



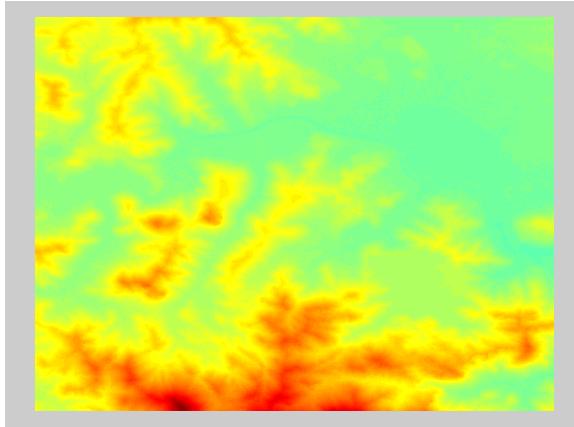
SAR and DTED to Identify Location of Strong Scatterers in the GMTI Range-Clutter Map



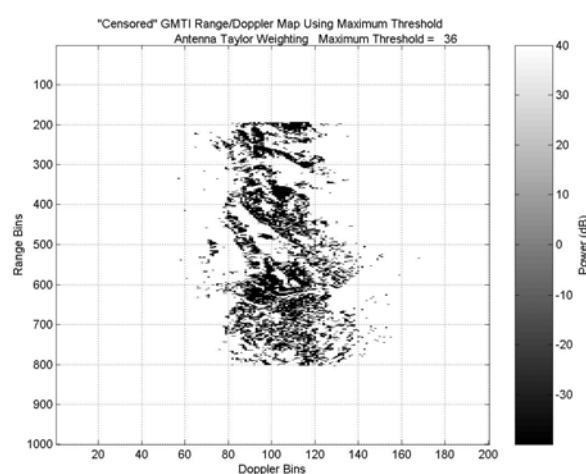
SAR Imagery: 3 m x 3 m Resolution



Synthesized GMTI Clutter Map:
10 m Range, 5 Hz Doppler Resolution



Level-3 DTED



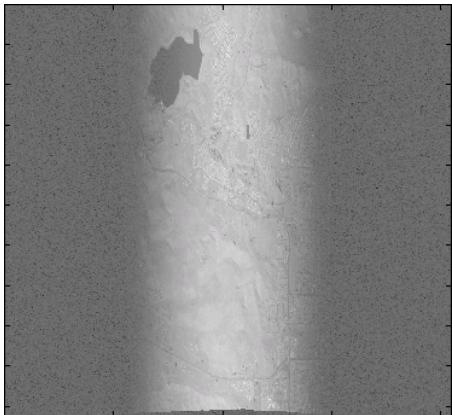
GMTI Range/Doppler Cells Whose Corresponding
SAR Magnitude Exceeds Threshold



KASSPER to Populate/Refine Database



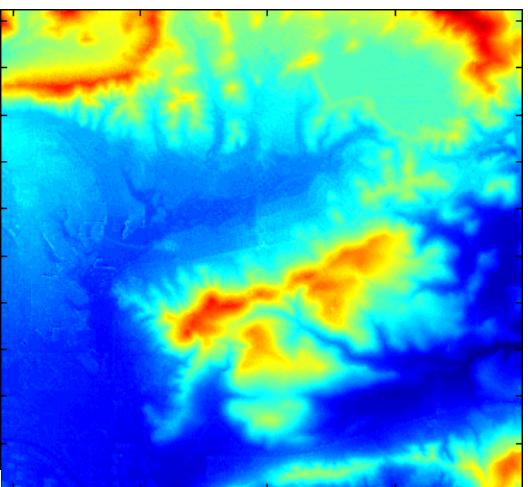
IFSAR MAGNITUDE



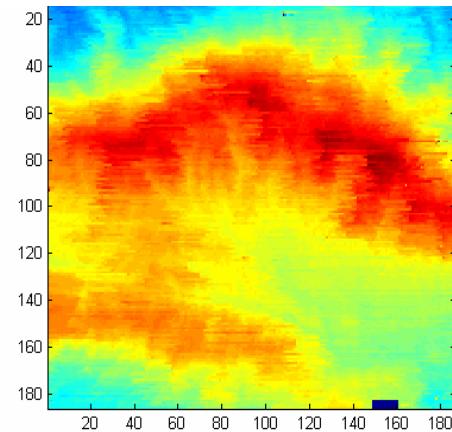
LOOK-1



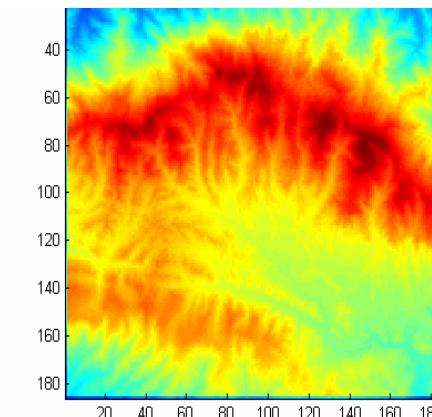
LOOK-2



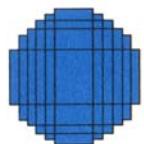
IFSAR HEIGHT



ESTIMATED
DEM



LEVEL-3
DTED



Technology
Service
Corporation



KASSPER: “It’s an Architecture, NOT an Algorithm”



*KASSPER is an architecture for **real-time** adaptation of multidimensional sensor systems in **real-world** environments*

- KASSPER Architecture
 - Environmental context is key to efficient adaptation
 - Sensors, like humans, benefit from context!
 - Key enablers: “look-ahead” scheduling and resource allocation
 - Multiresolution philosophy: blurring the boundaries between SAR and GMTI
 - KASSPER as a modern manifestation of the “Bayesian” method!
 - KA-STAP → Bayesian STAP
- The DARPA KASSPER Challenge: Creatively explore the possibilities
 - Re-examine entire adaptive signal processing paradigm with an eye towards maximizing knowledge-aided “robust” methods
 - Robust STAP algorithms AND KASSPER architecture
 - Environmental knowledge base is “read/write”
 - What is “implementable”? 2010? 2020?
 - Environmentally aware sensors have a future!